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Offsetting effects of aerosols on Arctic and global climate in the late 20th century

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Abstract

We examine the impacts of atmospheric aerosols on Arctic and global climate using a series of 20th century transient simulations from Community Climate System Model version 4 (CCSM4). We focus on the response of surface air temperature to the direct radiative forcing driven by changes in sulfate and black carbon (BC) concentrations from 1975 to 2005 and we also examine the response to sulfate, BC, and organic carbon aerosols varying at once. The direct forcing from sulfate dominates the aerosol climate effect. Globally averaged, all three aerosols produce a cooling trend of 0.015 K decade^{-1} during the period 1975–2005. In the Arctic, surface air temperature has large spatial variations in response to changes in aerosol concentrations. Over the European Arctic, aerosols induce about 0.6 K decade^{-1} warming which is about 1.8 K warming over the 30 yr period. This warming is triggered mainly by the reduction in sulfate and BC emissions over Europe since the 1970s and is reinforced by sea ice loss and a strengthening in atmospheric northward heat transport. Over the Siberian and North American Arctic, surface air temperature is likely influenced primarily by changes in aerosol emissions from Asia. An increase in sulfate emissions over Asia induces a large cooling while an increase in BC over Asia causes a significant warming.

1 Introduction

The Arctic (the region poleward of 60° N) has warmed dramatically since the 1970s, by ~ 1.5 °C. The warming in the Arctic is at least two times larger than the global mean temperature increase (e.g., Serreze et al., 2009). This phenomenon is known as Arctic amplification (e.g., Manabe and Stouffer, 1980). The detailed mechanisms causing the warming are not fully understood (Serreze and Barry, 2011). Climate model simulations have shown that ice-albedo feedback is likely to account for much of the Arctic warming (e.g., Holland and Bitz, 2003; Screen and Simmonds, 2010), whereby warmer

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temperatures cause highly reflective snow and sea ice to melt, decreasing the Earth's planetary albedo and thus inducing further warming.

While the snow/ice-albedo feedback triggered by greenhouse gas warming dominates Arctic warming, short-lived aerosols in the atmosphere also are an important forcing agent in this region (e.g., Quinn et al., 2008; Koch et al., 2009; Shindell and Faluvegi, 2009; Serreze and Barry, 2011). Further, climate changes triggered by aerosol trends will also be enhanced by the snow/ice-albedo feedback. Shindell and Faluvegi (2009) conducted sensitivity experiments using the GISS-ER climate model and suggested that decreasing concentrations of sulfate aerosols and increasing concentrations of BC have substantially contributed to Arctic warming over the last three decades. They also found Arctic temperature changes depend on the location of BC. Increasing concentrations of BC in low/mid-latitude causes warming in the Arctic, while increasing BC in the Arctic itself causes cooling in the Arctic. In another climate model study, Sand et al. (2013) produced similar results to Shindell and Faluvegi (2009) and attributed the response in Arctic surface air temperature mainly to the changes in atmospheric northward heat transport (NHT). Increasing atmospheric BC in the Arctic leads to a weakening of NHT and thus surface cooling; when located in mid-latitudes, NHT is strengthened leading to surface warming. Arctic surface temperature is also found to be sensitive to the vertical distribution of BC in the CCSM4 (Flanner, 2013): a layer of BC centered in the upper troposphere produces surface cooling, while a layer of BC in the lower troposphere causes weak surface warming. While there has been much focus on the role of BC in Arctic climate, we are interested in how Arctic climate has been affected by changes in both sulfate and BC aerosol distributions over the past three decades. As shown below trends in the two are not homogenous in either space or time.

Here, the response of Arctic and global surface air temperature to the trends of atmospheric sulfate and BC aerosols are examined using 20th century simulations from CCSM4. We performed single forcing experiments, in which only direct radiative forcing from sulfate aerosols or BC was included. This enables us to isolate the effects of

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sulfate and BC and their contributions to the effect of all aerosols on climate. We also examine the response to sulfate, BC, and organic carbon aerosols varying at once. In addition to surface air temperature, we investigate the response of sea level pressure, sea ice coverage, cloud radiative forcing and atmospheric NHT to determine the mechanisms that cause the surface air temperature change in the Arctic during the period 1975–2005.

2 Model and experiments

We use CCSM4 with fully coupled atmosphere, ocean, land and sea ice components (Gent et al., 2011). The atmosphere component is the Community Atmosphere Model 4 (CAM4) (Neale et al., 2011) with a horizontal resolution of $0.9^{\circ} \times 1.25^{\circ}$. The atmospheric aerosol concentrations were derived from an earlier version of CAM3 run with interactive chemistry and observationally-based estimates of reactive gas emissions (Lamarque et al., 2011). The same model and 20th century forcing datasets were used for the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012) contributions from CCSM4. Compared with Advanced Very High Resolution Radiometer (AVHRR) observations, Shindell et al. (2013) demonstrated that CAM4 captures total aerosol optical depth trends of 1980–2000 well over the areas of high aerosol emissions (e.g., Europe, eastern North America and south and east Asia). Note that the aerosol indirect effect is not included in CAM4, so the microphysical effects of aerosols on clouds are not included.

The sulfate-only and BC-only single forcing experiments were realized by prescribing the time- and space- evolving mass concentrations of sulfate and BC, respectively. All other forcings were kept fixed at 1850 levels, including surface depositions of BC on snow and sea ice. For each experiment, six branch runs were carried out from year 1920 and run to year 2005. The restart files of year 1920 were obtained from 20th century total aerosol forcing only integrations with CCSM4 for CMIP5 (see Meehl et al., 2012).

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Figure 1 shows linear trends in optical depths of sulfate and BC from 1975 to 2005. The results are ensemble means of six integrations. Since the 1970s, sulfate aerosol emissions decreased significantly in Europe and North America. However, emissions increased from Southeast of Asia, India and the Pacific Ocean region (Fig. 1a). Globally, there is a decrease in sulfate emissions (not shown). Due to the emissions reductions in Europe and North America, sulfate optical depth decreased over the Arctic, especially over the Eurasian Arctic (Fig. 1b). Sulfate aerosol is almost entirely scattering, with a single scattering albedo equal to one in the solar spectrum and a small fraction of absorption in the near-infrared spectrum. Therefore, it causes a net radiative cooling at the surface by scattering solar radiation back to space and letting less solar radiation reaching the surface (IPCC, 2007, p. 160). The mean surface radiative flux change in year 2000 due to sulfate is estimated at $-0.84\,\mathrm{W\,m^{-2}}$ globally and $-0.22\,\mathrm{W\,m^{-2}}$ for the Arctic in CCSM4 (not shown).

From 1975 to 2005 there were significant reductions in BC emissions in Europe, but over the same period there were significant increases in emissions in India and China (Fig. 1c). At the same time, emissions of fossil fuel BC declined in the US (IPCC, 2007, p. 163). Thus, the slight increase in BC optical depth over North America seen in Fig. 1c is possibly due to the downstream transport from Asia. In contrast, there was a decline in sulfate optical depth over North America and over all of the Arctic (Fig. 1a and b). While global mean sulfate emissions declined, BC emissions increased (not shown). In the Arctic, BC optical depth shows a negative trend over the European Arctic but a positive trend over the rest of the Arctic (Fig. 1d). BC is a light-absorbing aerosol, so it absorbs solar radiation and heats the surrounding air (IPCC, 2007, p. 163). The annual mean instantaneous flux change at the surface due to the direct effect of atmospheric BC is $-0.46\,\mathrm{W\,m^{-2}}$ over the whole globe and $-0.14\,\mathrm{W\,m^{-2}}$ over the Arctic in model year 2000 in CCSM4 (not shown).

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3 Results

3.1 Surface air temperature trends

Figure 2 depicts the time-evolving surface air temperature response to the change in all aerosols, sulfate-only and BC-only from 1920 to 2005. In addition to six simulations of sulfate-only forcing and six BC-only simulations that we conducted, we also include three runs of all three aerosol forcing at once and three runs of sulfate-only from CMIP5 (Meehl et al., 2012). The all aerosol, sulfate-only and BC-only runs have ensemble members of three, nine and six, respectively. The 1850 control run was also obtained from CMIP5. Globally, surface air temperature from sulfate-only forcing resembles that of the all aerosol forcing, with a significant negative trend of about 0.02 K decade^{-1} 1920–2005 and $\sim$ 0.015 K decade^{-1} 1975–2005 in CCSM4. Therefore, the response of global surface air temperature to all aerosols is dominated by the direct forcing by sulfate. BC has a warming effect on global temperature ($\sim$ 0.1 K), but this is almost completely offset by the cooling influence from organic carbon, which is co-emitted with BC (e.g., Bond et al., 2013). In the Arctic, surface air temperature is more variable, with no clear trends in Arctic-averaged surface air temperature from 1975 to 2005 in any of the three cases. The BC-only case indicates some warming from 1980 to 2000, followed by a cooling 2000–2010, but this is not statistically significant. However, there were statistically significant positive and negative temperature trends in different regions of the Arctic, which in this Arctic-wide average offset each other.

Geographic distributions of surface air temperature trends 1975–2000 are shown in Fig. 3. We focus primarily on the changes in the Arctic, but show the global maps to aid interpretation of what is driving the Arctic changes. Direct radiative forcing by all aerosols produces a pronounced warming of 0.6 K decade^{-1} over the European Arctic, a cooling of 0.6 K decade^{-1} over the Russian Arctic and a sight warming over the North American Arctic (Fig. 3a and b). In the sulfate-only experiment, there is a strong warming of 0.4 K decade^{-1} over the European and western Eurasian Arctic (Fig. 3c and d) where sulfate concentrations have declined (Fig. 1a). In and downstream of Siberia

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and in the western US there is a significant cooling, which is contrary to what would be expected, given that sulfate concentrations decreased across this region (Fig. 1). Thus, this cooling must be a response to forcing in other regions. In BC-only simulations (Fig. 3e and f), surface air temperatures warm 0.2 K decade^{-1} over the European Arctic, presumably in response to a reduction in BC concentrations. There is a pronounced warming of roughly 0.4 K decade^{-1} over the Siberian and Alaskan Arctic and a strong cooling over the far north Atlantic despite small increases in BC optical depth in these regions. While there is some correspondence between change in aerosol optical depths (Fig. 1) and surface air temperatures (Fig. 3), the two are not perfectly correlated. This is because, in addition to the instantaneous impact of aerosols on radiative fluxes, there are climate responses to the forcings which themselves affect surface air temperatures. In some cases, quite long-range connections are possible. Previous studies (Shindell and Faluvegi, 2009; Sand et al., 2013; Flanner, 2013) regarding the role of remote aerosols on Arctic temperatures show that an increase in BC concentrations at low latitudes causes a warming in the Arctic. Such remote influence is also shown by Teng et al. (2012) who found surface warming over the Siberian Arctic in response to increasing BC concentrations in Asia in CCSM4 (see their Fig. 2).

3.2 Interpreting the climate responses to forcing

To further understand the temperature trends we analyzed sea level pressure, sea ice coverage, radiative fluxes changes at top of the atmosphere (TOA) due to changes in clouds and changes in NHT using the transient sulfate-only and BC-only runs as described in Sect. 2. NHT is calculated following Eq. (1) in Sand et al. (2012). In the sulfate-only experiment (Fig. 4a–d), there is a dipole in sea level pressure trends, i.e. in the eastern North Atlantic vs. in the European and west Eurasian Arctic. This draws warmer air northward from lower latitudes, consistent with the strong warming trend found in the European Arctic. The significant sea ice loss over the Barents Sea amplifies the warming there. Surface cooling over most of the rest of the Arctic is consistent with cold-air advection from Siberia, amplified by sea ice gain on the Siberian shelf

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and into the Chukchi and Beaufort Sea. Net changes in cloud radiative fluxes at TOA, which are the summation of shortwave and longwave fluxes, have a similar pattern to the changes in sea ice coverage. These show a radiative cooling effect over the European Arctic and warming over Siberia. NHT enhances the warming over the Eurasian Arctic and the cooling over the Siberian and North American Arctic. These findings suggest that direct surface radiative cooling from sulfate aerosols is the possible trigger for the surface cooling while the dynamical response of atmospheric circulation, sea ice, and clouds work together to reinforce such temperature trends. Cloud changes have a weaker influence than sea ice and NHT changes in terms of magnitudes of trends. Again, we emphasize that the cloud changes produced here are only due to a thermodynamic response to the aerosol direct radiative forcing. If cloud microphysical effects were included in the model runs cloud changes might have a much more significant impact on Arctic climate.

The dynamical response of the atmosphere and sea ice are similarly important in the BC-only experiment (Fig. 4e–h). Sea ice coverage decreases near the Barents Sea and the eastern Siberia shelf, where surface air temperature increases. NHT has strong positive trends over the Eurasian and North American Arctic. Therefore, the responses in both sea ice and NHT to aerosol direct radiative forcing reinforce the surface air temperature changes. Trends in net cloud radiative fluxes are weak and do not show a clear pattern.

4 Summary and discussion

We use fully coupled CCSM4 with CAM4 physics to investigate the Arctic and global climate response to the change in concentrations of all aerosols, sulfate aerosols only and BC only during the three decades from 1975 to 2005. Single-forcing transient simulations were performed in order to insolate the impacts of all aerosols, sulfate only and BC only. The surface air temperature response to all aerosols is dominated by changes in sulfate, with the effects of BC are apparently mostly offset by coincident

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trends in organic carbon. Globally averaged, trends in all aerosols produce a cooling trend of 0.015 K decade^{-1} during the period of 1975–2005, with 0.02 K decade^{-1} cooling driven by changes in sulfate aerosols. Averaged across the whole Arctic, surface air temperature shows no significant trend. However, there are pronounced geographical variations in temperature trends. Over the European Arctic, aerosols induce about 0.6 K decade^{-1} warming, or about 1.8 K warming over the 30 yr period from 1975 to 2005. This warming is triggered by a reduction in sulfate and BC concentrations over that region and is maintained by sea ice loss and a strengthening in NHT. Changes in sulfate concentrations account for about two thirds of the warming and BC for the remaining one-third. Over the Siberian and North American Arctic, surface air temperature is likely influenced primarily by aerosols transported from Asia. An increase in sulfate emissions over Asia induces a large cooling while an increase in BC over Asia causes a significant warming, consistent with Shindell and Faluvegi (2009). Thus, full understanding of drivers of Arctic climate change require accounting for changes in all aerosol species – not just BC – and of the climate responses to both local and remote forcings.

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References

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M. Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and Zenderm C. S.: Bounding the role of black

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13, 30929–30943, 2013

carbon in the climate system: a scientific assessment, J. Geophys. Res.-Atmos., 118, 5380–5552, doi:10.1002/jgrd.50171, 2013.
Flanner, M. G.: Arctic climate sensitivity to local black carbon, Geophys. Res., 118, 1840–1851, doi:10.1002/jgrd.50176, 2013.
Gent, P. R., Danabasoglu, G., Donner, L. J., Holland, M. M., Hunke, E. C., Jayne, S. R., Lawrence, D. M., Neale, R. B., Rasch, P. J., Vertenstein, M., Worley, P. H., Yang, Z.-L., and Zhang, M.: The community climate system model version 4, J. Climate, 24, 4973–4991, doi:10.1175/2011JCLI4083.1, 2011.
Holland, M. M. and Bitz, C. M.: Polar amplification of climate change in the coupled model intercomparison project, Clim. Dynam., 21, 221–232, 2003.
Koch, D. and Hansen, J.: Distant origins of Arctic black carbon: a Goddard Institute for Space Studies model experiment, J. Geophys. Res., 110, D04204, doi:10.1029/2004JD005296, 2005.
Koch, D., Menon, S., Genio, A. D., Ruedy, R., Alienov, I., and Schmidt, G. A.: Distinguishing aerosol impacts on climate over the past century, J. Climate, 22, 2659–2677, 2009.
Lamarque, J.-F., Kyle, G. P., Meinshausen, M., Riahi, K., Smith, S. J., van Vuuren, D. P., Conley, A., and Vitt, F.: Global and regional evolution of short-lived radiatively-active gases and aerosols in the representative concentration pathways, Climatic Change, 109, 191–912, doi:10.1007/s10584-011-0155-0, 2011.
IPCC: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.
Manabe, S. and Stouffer, R. J.: Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere, J. Geophys. Res., 85, 5529–5554, 1980.
Meehl, G. A., Washington, W. M., Arblaster, J. M., Hu, A., Teng, H., Tebaldi, C., Sanderson, B. N., Lamarque, J.-F., Conley, A., Strand, W. G., and White III, J. B.: Climate system response to external forcings and climate change projections in CCSM4, J. Climate, 25, 3661–3683, 2012.
Neale, R. B., Richter, J. H., Conley, A. J., Park, S., Lauritzen, P. H., Gettelman, A., Williamson, D. L., Rasch, P. J., Vavrus, S. J., Taylor, M. A., Collins, W. D., Zhang, M., and Lin, S.-J.: Description of the NCAR Community Atmosphere Model (CAM4), NCAR Tech. Rep.

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13, 30929–30943, 2013

NCAR/TN-485+STR, 212 pp., available at: https://www.ccsm.ucar.edu/models/ccsm4.0/cam/docs/description/cam4_desc.pdf, 2011.

Quinn, P. K., Bates, T. S., Baum, E., Doubleday, N., Fiore, A. M., Flanner, M., Fridlind, A., Garrett, T. J., Koch, D., Menon, S., Shindell, D., Stohl, A., and Warren, S. G.: Short-lived pollutants in the Arctic: their climate impact and possible mitigation strategies, Atmos. Chem. Phys., 8, 1723–1735, doi:10.5194/acp-8-1723-2008, 2008.

Sand, M., Berntsen, T. K., Kay, J. E., Lamarque, J. F., Seland, Ø., and Kirkevåg, A.: The Arctic response to remote and local forcing of black carbon, Atmos. Chem. Phys., 13, 211–224, doi:10.5194/acp-13-211-2013, 2013.

Screen, J. A. and Simmonds, I.: The central role of diminishing sea ice in recent Arctic temperature amplification, Nature, 464, 1334–1337, 2010.

Serreze, M. C. and Barry, R. G.: Processes and impacts of Arctic amplification: a research synthesis, Global Planet. Change, 77, 85–96, doi:10.1016/j.gloplacha.2011.03.004, 2011.

Serreze, M. C., Barrett, A. P., Stroeve, J. C., Kindig, D. N., and Holland, M. M.: The emergence of surface-based Arctic amplification, The Cryosphere, 3, 11–19, doi:10.5194/tc-3-11-2009, 2009.

Shindell, D. and Faluvegi, G.: Climate response to regional radiative forcing during the twentieth century, Nat. Geosci., 2, 294–300, doi:10.1038/ngeo473, 2009.

Shindell, D. T., Lamarque, J.-F., Schulz, M., Flanner, M., Jiao, C., Chin, M., Young, P. J., Lee, Y. H., Rotstayn, L., Mahowald, N., Milly, G., Faluvegi, G., Balkanski, Y., Collins, W. J., Conley, A. J., Dalsoren, S., Easter, R., Ghan, S., Horowitz, L., Liu, X., Myhre, G., Nagashima, T., Naik, V., Rumbold, S. T., Skeie, R., Sudo, K., Szopa, S., Takemura, T., Voulgarakis, A., Yoon, J.-H., and Lo, F.: Radiative forcing in the ACCMIP historical and future climate simulations, Atmos. Chem. Phys., 13, 2939–2974, doi:10.5194/acp-13-2939-2013, 2013.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An overview of CMIP5 and the experiment design, B. Am. Meteorol. Soc., 93, 485–498, doi:10.1175/BAMS-D-11-00094.1, 2012.

Teng, H., Washington, W. M., Branstator, G., Meehl, G. A., and Lamarque, J.-F.: Potential impacts of Asian carbon aerosols on future US warming, Geophys. Res. Lett., 39, L11703, doi:10.1029/2012GL051723, 2012.

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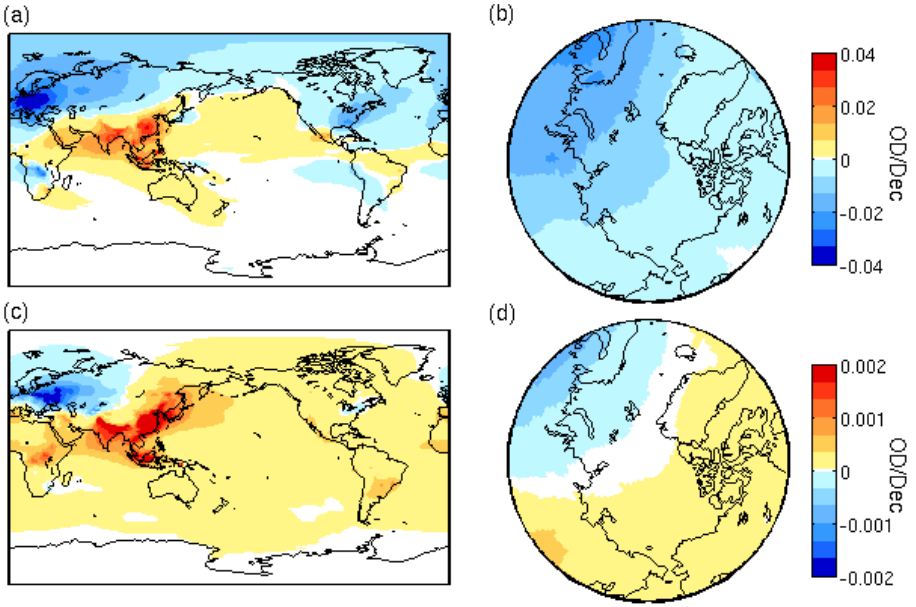

Fig. 1. Linear trends in optical depths per decade for sulfate **(a, b)** and black carbon **(c, d)** for the period 1975–2005, both globally and for the Arctic.

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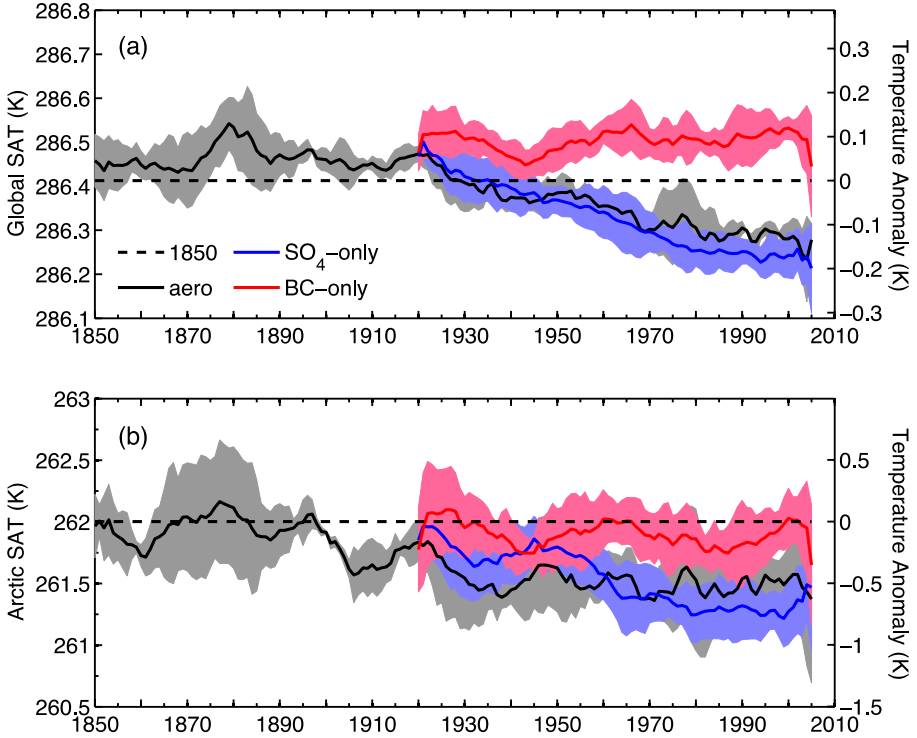

Fig. 2. Time series of area-weighted, annual-mean surface air temperature (SAT) over the globe **(a)** and Arctic **(b)** for all aerosol forcing (black), sulfate-only forcing (blue) and BC-only forcing (red). Shading indicates one standard deviation of ensemble members. A 9 yr running mean was applied. A year 1850 control run is shown in black dashed line.

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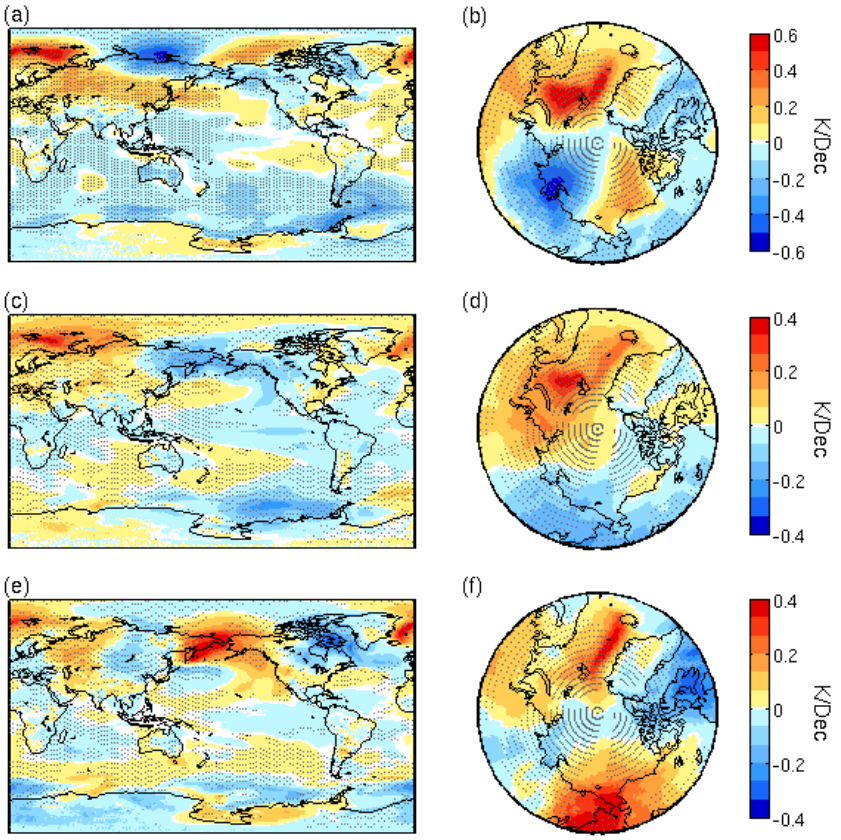

Fig. 3. Linear trends in surface air temperature for the period 1975–2005 over the globe and Arctic due to changes in all aerosols (**a** and **b**), sulfate only (**c** and **d**) and black carbon only (**e** and **f**), respectively. Gray dots indicate trends that are statistically significant at the 95 % level ($p < 0.05$) based on an F test.

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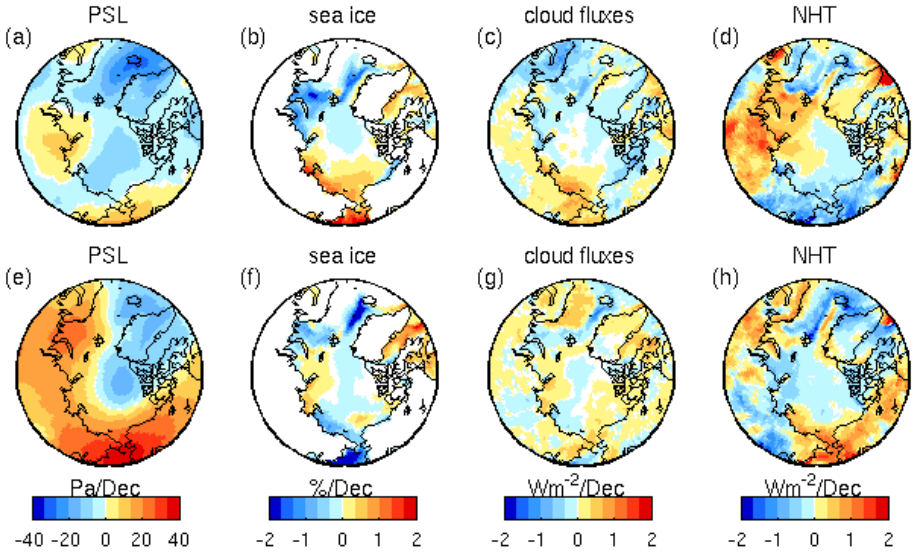

Fig. 4. Linear trends in sea level pressure (PSL), sea ice coverage, cloud net radiative fluxes at top of the atmosphere, and atmospheric northward heat transport (NHT) over the period 1975–2005 in the Arctic due to direct radiative forcing by sulfate only **(a–d)** and black carbon only **(e–h)**, respectively.

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